Preliminary Estimate of Effective Ground-Water Recharge Rates in Central Oklahoma

by

Wayne A. Pettyjohn

and
Andrew Miller

Department of Geology
Oklahoma State University
Stillwater, OK 74078

Presented To The

Oklahoma Water Resources Board
Oklahoma City, OK

-June 1982-

ABSTRACT

Ground-water recharge rates for the unconfined part of the Garber-Wellington Aquifer in central Oklahoma were estimated for water years 1973, 1976, 1978, and 1979 by means of a computerized stream hydrograph separation technique. Although many factors influence recharge rates, it would appear that, on the average, about 100,000 gallons per day per square mile, or about 2.11 inches, of water infiltrates the aquifer and then finds its way to a nearby stream.

Preliminary Estimate of Effective Ground-Water Recharge Rates in Central Oklahoma

by

Wayne A. Pettyjohn

and

Andrew Miller

Department of Geology

Oklahoma State University

Stillwater, OK

Introduction

The Oklahoma Water Resources Board is investigating the Garber-Wellington aquifer system, which is the major source of water supply for municipalities and industries in Central Oklahoma. This report is a small part of the overall project and its purpose is to estimate the rate at which precipitation infiltrates and reaches the water table (ground-water recharge rate) in the unconfined part of the aquifer. The analysis is based on a computer program that separates stream flow into its two major components-surface runoff and ground-water runoff.

General Features of the Area

The study area, which includes the outcropping rocks of the Garber-Wellington aquifer, lies in Central Oklahoma between 96° and 98° longitude (plate 1). The region is characterized by a gently eastward sloping surface of rolling grass covered prairie and low wooded hills. It includes about 23,000 square miles, although the drainage area is considerably larger.

Annual precipitation in Oklahoma ranges from more than 56 inches in the southeast to less than 14 inches in the western part of the panhandle (fig. 1). The average annual precipitation rate is about 32 inches. The greatest amount of precipitation generally occurs in May while January is typically the driest month.

Although Oklahoma is subhumid, annual lake evaporation ranges from about 46 inches in the northeast to more than 56 inches in the northwest (fig. 2). Since evaporation exceeds precipitation throughout most of the state, much of the time there is a soil-moisture deficiency and ground-water recharge is not great.

Average annual runoff in Oklahoma ranges from less than 0.2 inches in the panhandle to more than 20 inches in the extreme southeast (fig. 3). Runoff is closely related to precipitation and evapotransipiration.

Geology of the Area

In Central Oklahoma bedrock dips 30 to 40 feet per mile westward toward the Anadarko Basin. Cropping out through much of this area (plate 1) is the Garber-Wellington aquifer, which consists of about 900 feet of interbedded sandstone, siltstone, and shale representing delta deposits. The Garber-Wellington is Early Permian in age.

The sediments were deposited by westerly flowing streams, which had their major axis at about the same latitude as Oklahoma City. As a result, the ratio of sandstone to shale reportedly decreases both northward and southward from this area. Furthermore, there is also a downdip or westward decrease in grain size from predominantly sandstone to predominantly shale.

The aquifer consists of channel sandstone deposits that are interfingered with shale units. Due to the nature of the deposits, abrupt changes in lithology are common. The maximum thickness of any one sandstone unit is

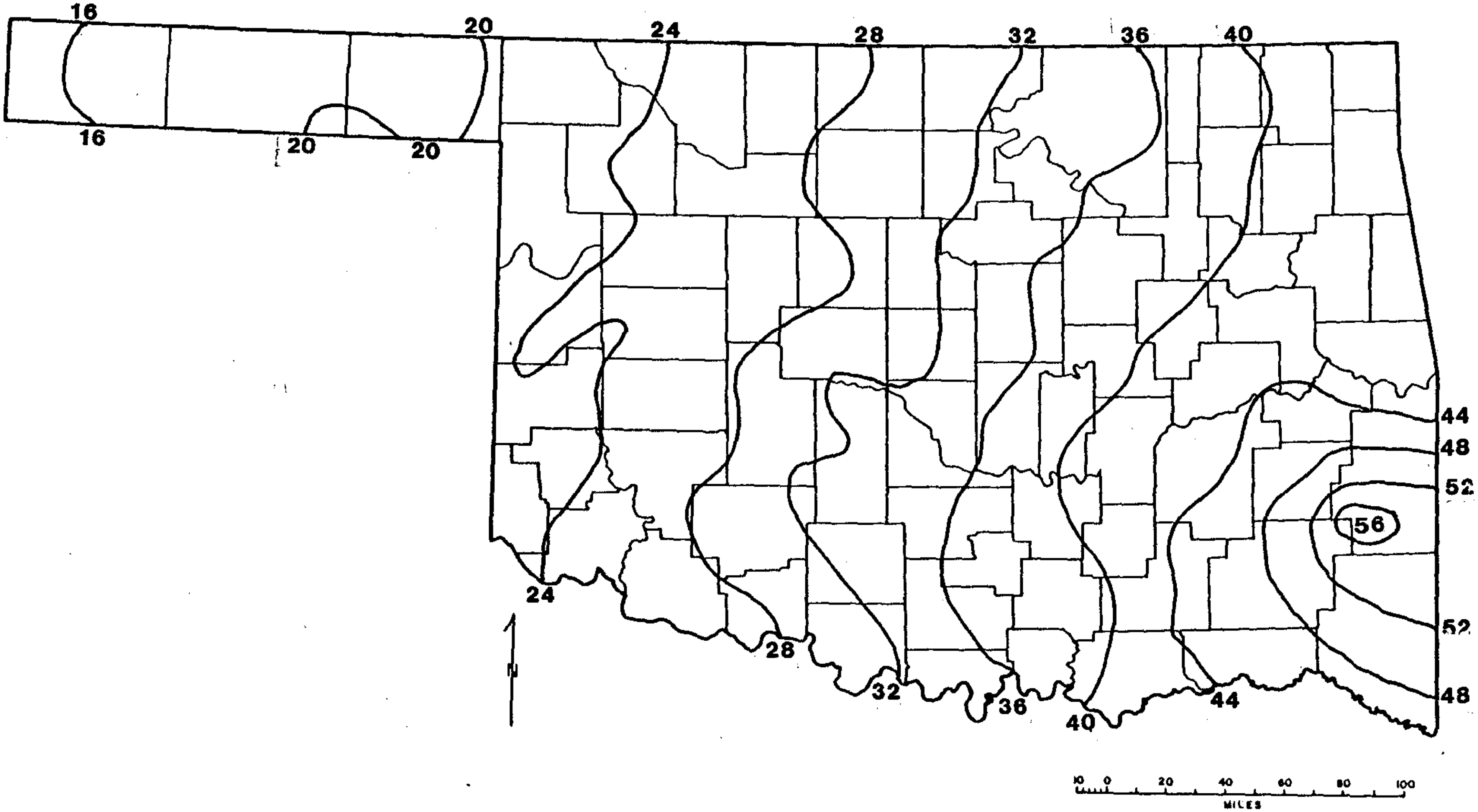


Figure 1. Average annual precipitation in Oklahoma, in inches for the period 1931-1960 (Modified from Oklahoma Water Resources Atlas, 1976).

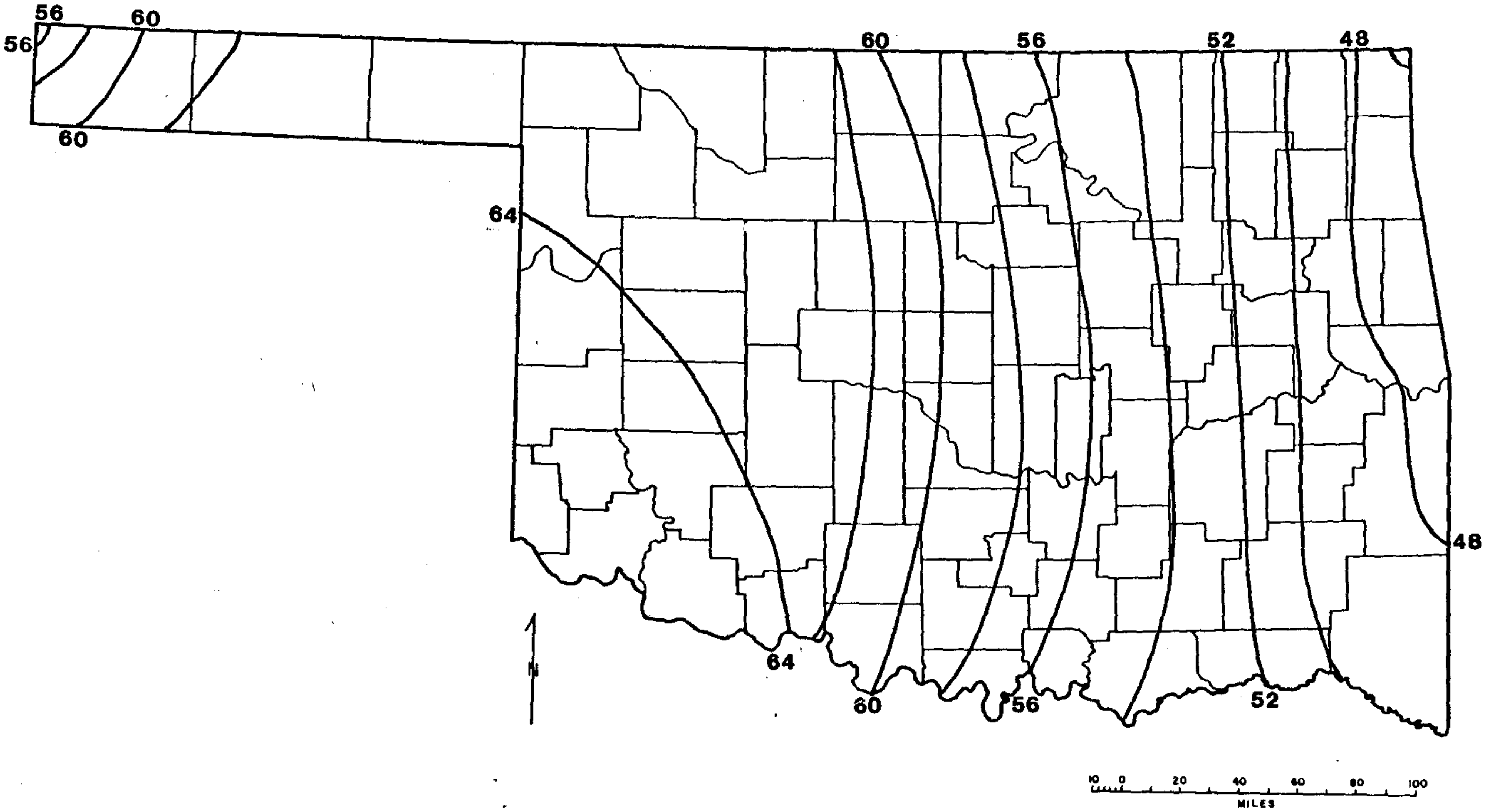


Figure 2. Average annual lake evaporation, in inches for the period 1946-1955 (Modified from Oklahoma Water Resources Atlas, 1976).

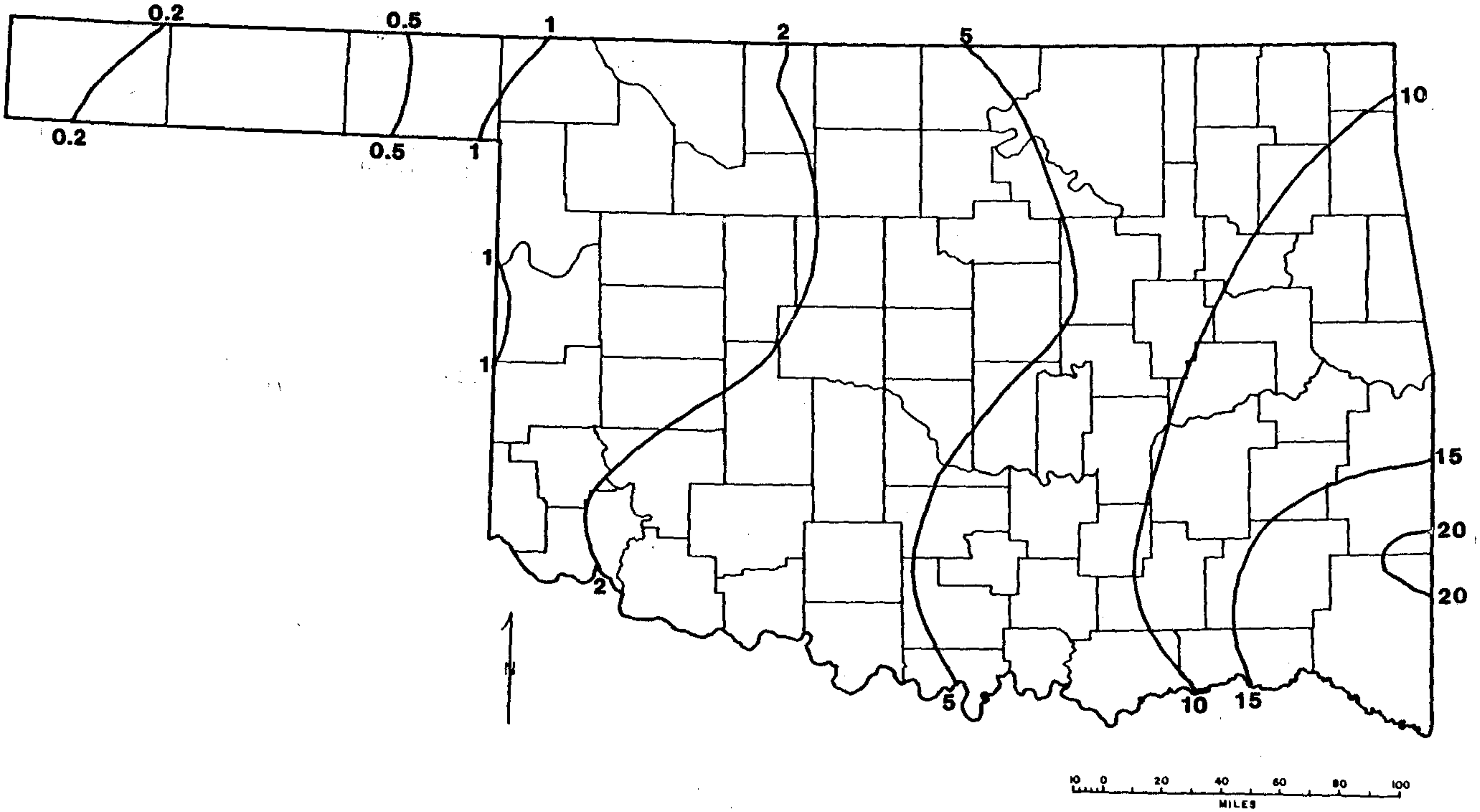


Figure 3. Average annual runoff, in inches for the period 1931-1960 (Modified for Oklahoma Water Resources Atlas, 1976).

about 40 feet, but they generally range between 5 and 10 feet. Shale layers, which average about 5 feet in thickness, have a maximum thickness of about 50 feet. Sandstone makes up about half of the aquifer, although this lithology ranges from about 30 to 75 percent of the total unit. The maximum amount of sandstone relative to shale is in the vicinity of Oklahoma City. The sandstone is typically fine grained, crossbedded, and reddish brown (see figures 4-17). Locally zones of muddy conglomerates and coarse-grained sand are present.

In the western part of the study area the Garber-Wellington is confined and is covered by the Hennessey Group, which is also Early Permian in age. In these areas recharge must find its way through the shale, migrate downdip or leak from adjacent units. The Hennessey Group consists largely of shale and siltstone, with some thin layer of very fine-grained sandstone. In some areas both the Garber-Wellington and Hennessey Group are overlain by alluvium and terrace deposits. In general, streams fed by discharge from the Garber-Wellington are perennial, whereas streams draining the Hennessey Group flow only during and a short while after precipitation.

The Garber Sandstone and Wellington Formation have similar water-bearing properties, are hydrologically interconnected, and are considered as a single aquifer. Water-table conditions exist in outcrop areas and reportedly in the upper 200 feet of the aquifer. At depths greater than 200 feet and beneath the Hennessey Group, the aquifer is semi-confined or confined. Transmissivity values obtained from aquifer tests range from 3,000 to 7,000 gallons per day per foot, while specific capacities average about 1.3 gallons per minute per foot of drawdown. Well yields, which range from 70 to 475 gallons per minute, average 245.

The deeper parts of the Garber-Wellington aquifer contain water with a

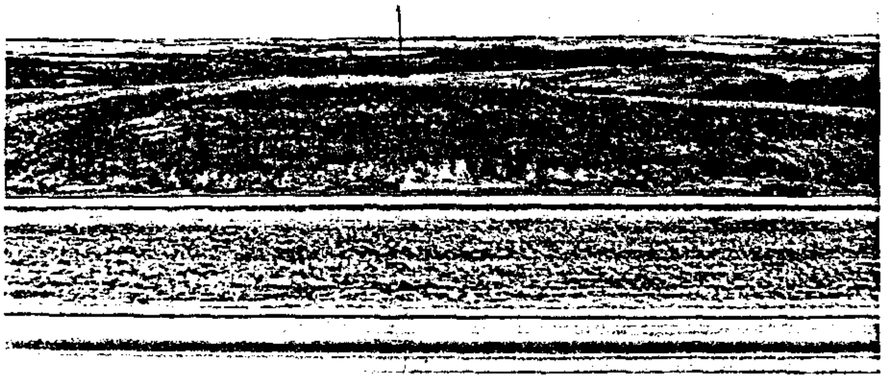


Figure 4. Red to dark brown sandstone interbedded with shale, which is typical of the Garber-Wellington Formation. The background topography is common in the study area.

Figure 5. Cimarron River at I-35. Alluvial deposits and rolling topography of study area.

Figure 6. Typical topography of areas underlain by Garber Sandstone near Guthrie.

Figure 7. Garber sandstone in an I-35 road cut north of Oklahoma City.

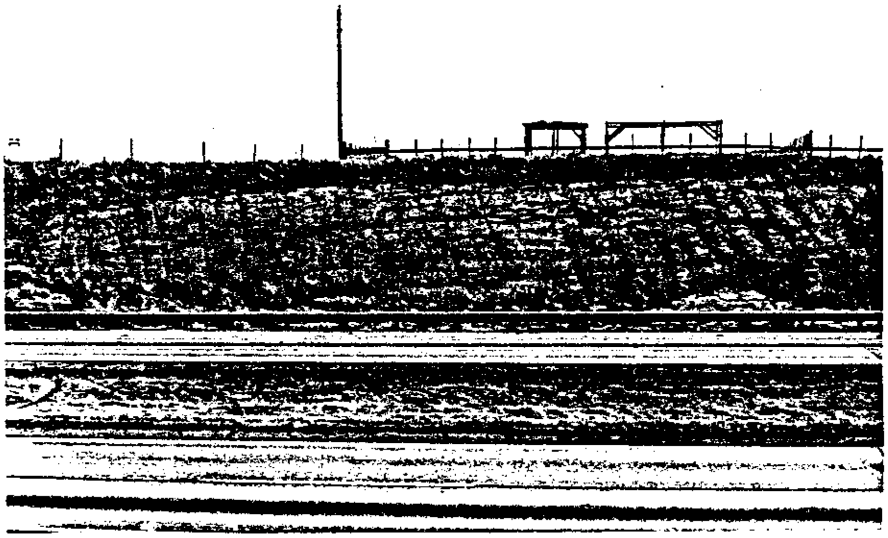


Figure 8. Massive lenses of Garber sandstone in a road cut near I-35 north of Oklahoma City.

Figure 9. Rocks typical of Garber-Wellington Formation. Cross-bedded sandstone above shale. Road cut on I-35 north of Oklahoma City.

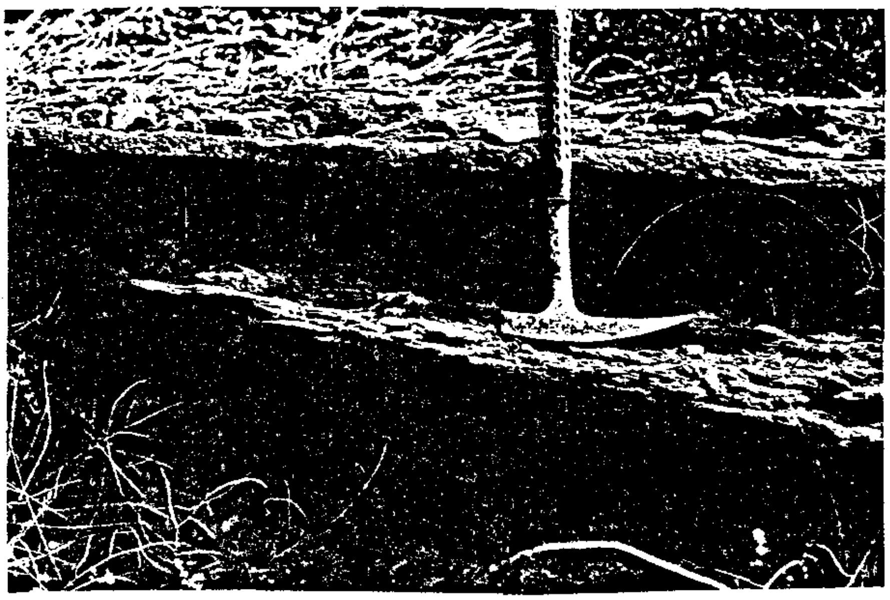


Figure 10. Interbedded sandstone and shale of the Garber-Wellington Formation. Road cut north of Oklahoma City on I-35.

Figure 11. Stream northeast of Oklahoma City cutting through collovium on top of the Garber-Wellington.

Figure 12. Road cut northeast of Oklahoma City. Cross-bedded sandstone with associated shale of the Garber-Wellington Formation.

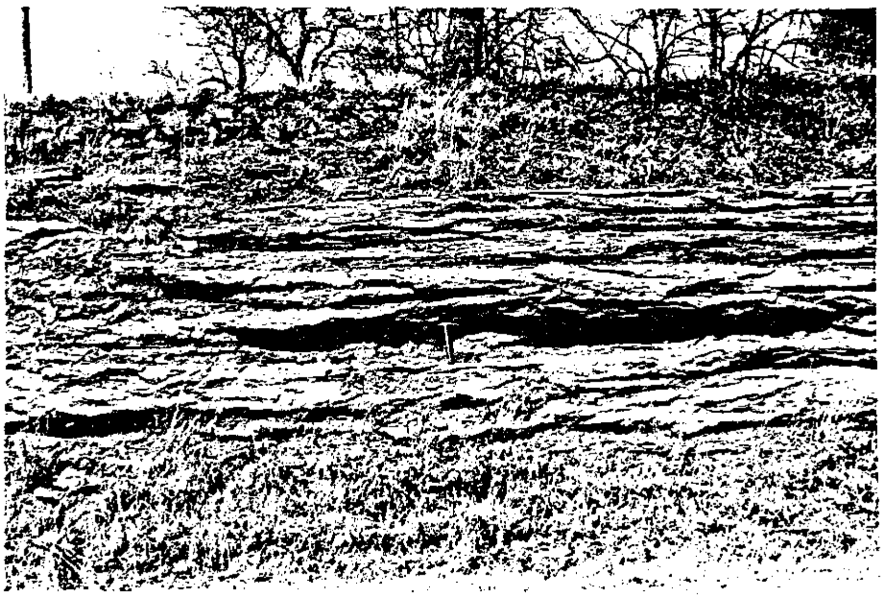


Figure 13. Interbedded fine sandstone and shale of the Garber-Wellington in a road cut northeast of Oklahoma City.

Figure 14. Cimarron River at the Payne-Logan County line. Wide alluvial deposits of fine sand.

Figure 15. Cimarron River at the Payne-Logan County line. Wide alluvial deposits of fine sand.

Figure 16. Wildhorse Creek at Highway 33 where it cuts through colluvium that overlie the Garber-Wellington.

Figure 17. Perkins Terrace, one mile west of Perkins. Sand dunes consisting of fine, permeable sand overlying the Garber-Wellington.

dissolved solids concentration in excess of 1,000 mg/l. Hardness is greatest in the upper parts of the aquifer, and the concentration of sulfate, chloride, and dissolved solids increase with depth. Overall, the quality of the water is considered good for an area of limited rainfall.

Floodplain deposits exert a major influence on stream flow in the region. These deposits are commonly sand, several to several tens of feet thick, and highly variable in width and length (plate 1). In many areas the floodplain deposits are hydrologically connected to adjacent sand dunes and form an extensive, permeable hydrologic system. In these areas there is likely to be but little surface runoff since most of the precipitation quickly infiltrates.

Alluvial deposits influence stream discharge for two major reasons. First they are major recharge areas. Secondly they tend to damp river stage fluctuations since part of the streamflow during periods of rising stage infiltrate the banks and temporarily remain there as bank storage until the stage falls.

Methods of Investigation

This preliminary estimate of natural recharge to the Garber-Wellington aquifer is based on the assumption that the precipitation that infiltrates and reaches the water table in the zone of intensive circulation eventually discharges to streams. It is this ground-water runoff that causes a stream to flow during dry periods. A much larger percentage of precipitation that infiltrates is taken up as soil moisture and eventually returns to the atmosphere by evaporation and transpiration. A very small amount of water that reaches the water table is withdrawn by wells; this component is not considered in this analysis because it is minute when compared to ground-water runoff.

In order to determine effective ground-water recharge rates, it is necessary to separate a stream hydrograph into surface runoff and ground-water runoff. This is accomplished by a method developed and described by Pettyjohn and Henning (1979). Ground-water runoff is assumed to equal effective ground-water recharge.

This particular technique was used successfully in a study that included the entire state of Ohio. It has been used elsewhere also, but not in a region that is hydrologically similar to Oklahoma. Presumably the technique is transferable, but it has not been proven by other methods. For this reason the natural recharge rates described herein must be used carefully.

The effective recharge rates described herein are determined by three other different methods; the sliding method, fixed interval method, and local minimum. Generally two of the three methods provide results that are in close agreement, while the third may differ considerably. This is due to differences in the hydrology of the basin, particularly the effect of streamside deposits. Where these contain permeable materials and influence bank storage, as is generally the case in Central Oklahoma, the sliding and fixed interval methods provide the most comparable results.

The long term precipitation pattern also has an effect on streamflow and ground-water runoff. For example, if there has been two or three years of below normal precipitation followed by a wet year, as in the case of water year 1973, the calculated recharge rates will be lower than a wet year that has been preceeded by two or three years of normal precipitation. The opposite is also true. This effect is related to replacement of both soil moisture and ground-water storage. Because of variable climate situations, recharge rates will also vary from one year to the next.

Investigative Results

Precipitation data from stations at Enid, Okemah, and Pauls Valley were examined for the years 1973, 1976, 1978 (fig. 18), and 1979. Except for 1979 these years were suggested by the Oklahoma Water Resources Board as being indicative of wet, dry, and normal years of precipitation. As shown in figures 19, 20, and 21, 1973 was above normal and 1976 was unusually dry, but 1978, rather than being normal at these three stations, was only slightly wetter or dryer than 1976, as far as average annual preicpitation is concerned. For these reasons water year 1979 was examined. Monthly precipitation of these stations is shown in Figurs 22, 23, and 24.

A soils map of Oklahoma was greatly generalized in order to focus more clearly on areas that should have higher natural rates of recharge (fig. 25). The category with the highest potential for natural recharge contains sandy soils and generally sandy subsoils. Most of these lie in the southern and eastern parts of the area. The area of sandy soils that commonly have fine grained subsoils have a moderate to low potential for recharge. These generally occur along or adjacent to the major rivers. Clayey soils are generally dark with clayey subsoils, although in some places they consist of loamy soils and loamy subsoils in loamy redbeds or alluvium. As a general rule, they have the least potential for natural recharge and cover a large percentage of the study area. On the basis of the map in Figure 25, one would assume, all other factors being equal, that the greatest amount of natural recharge to the Garber-Wellington would occur in the southern and east-central parts of the study area and adjacent to the major rivers.

Records of 21 gaging stations were examined for water years 1973 (wet), 1976 (dry), and 1978 and 1979 (normal), although records for all gages were not available for all of the years. Remarks concerning these gages are given

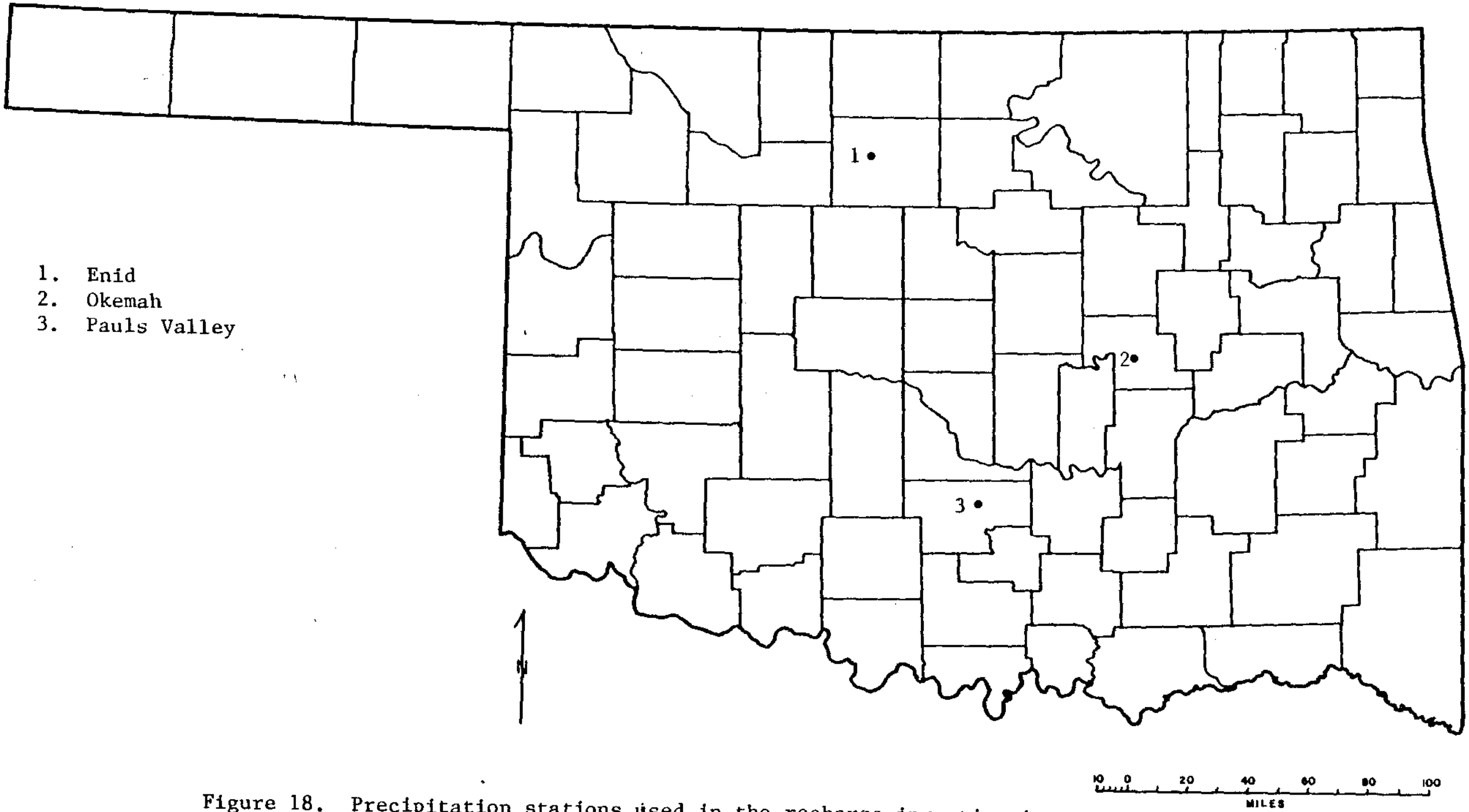


Figure 18. Precipitation stations used in the recharge investigation.

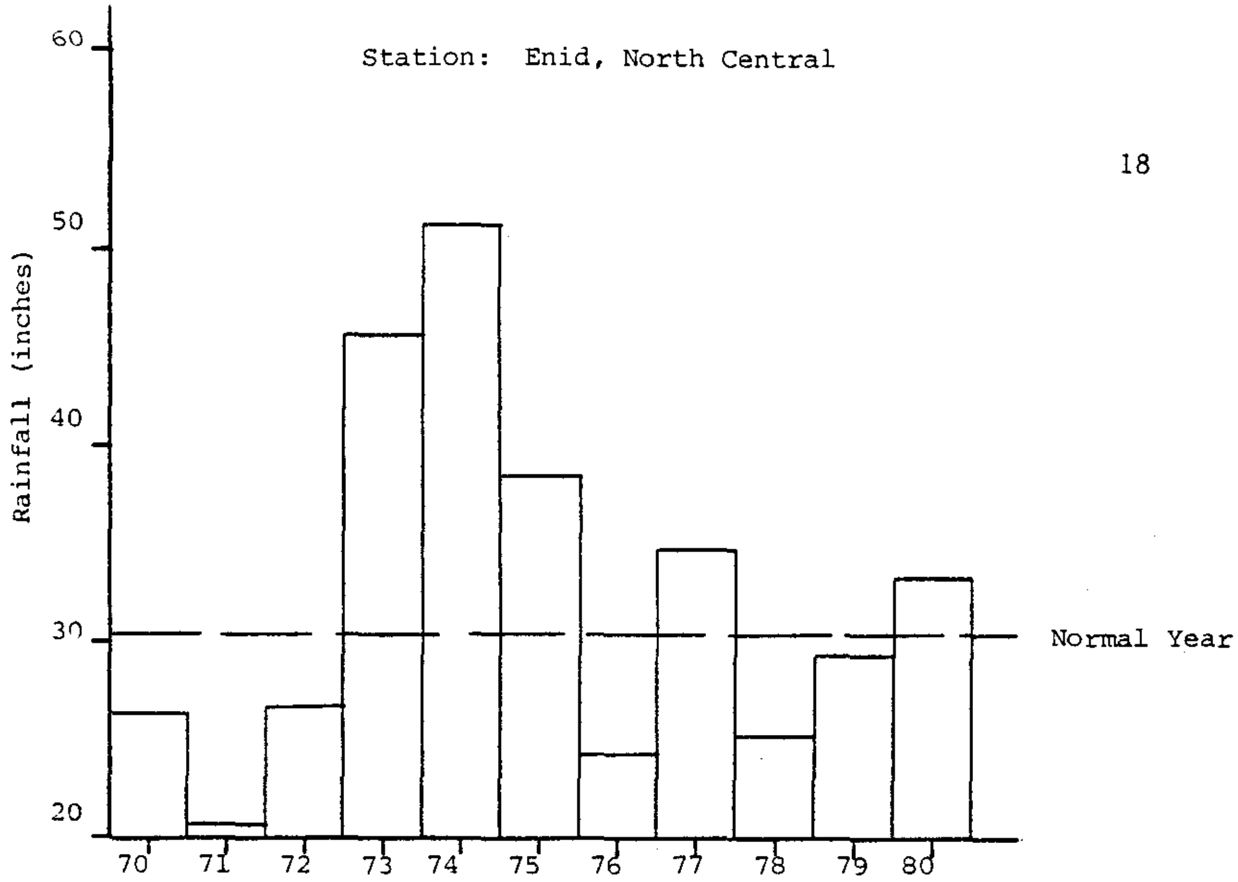


Figure 19. Mean Annual Precipitation for Water Years 1970-1980.

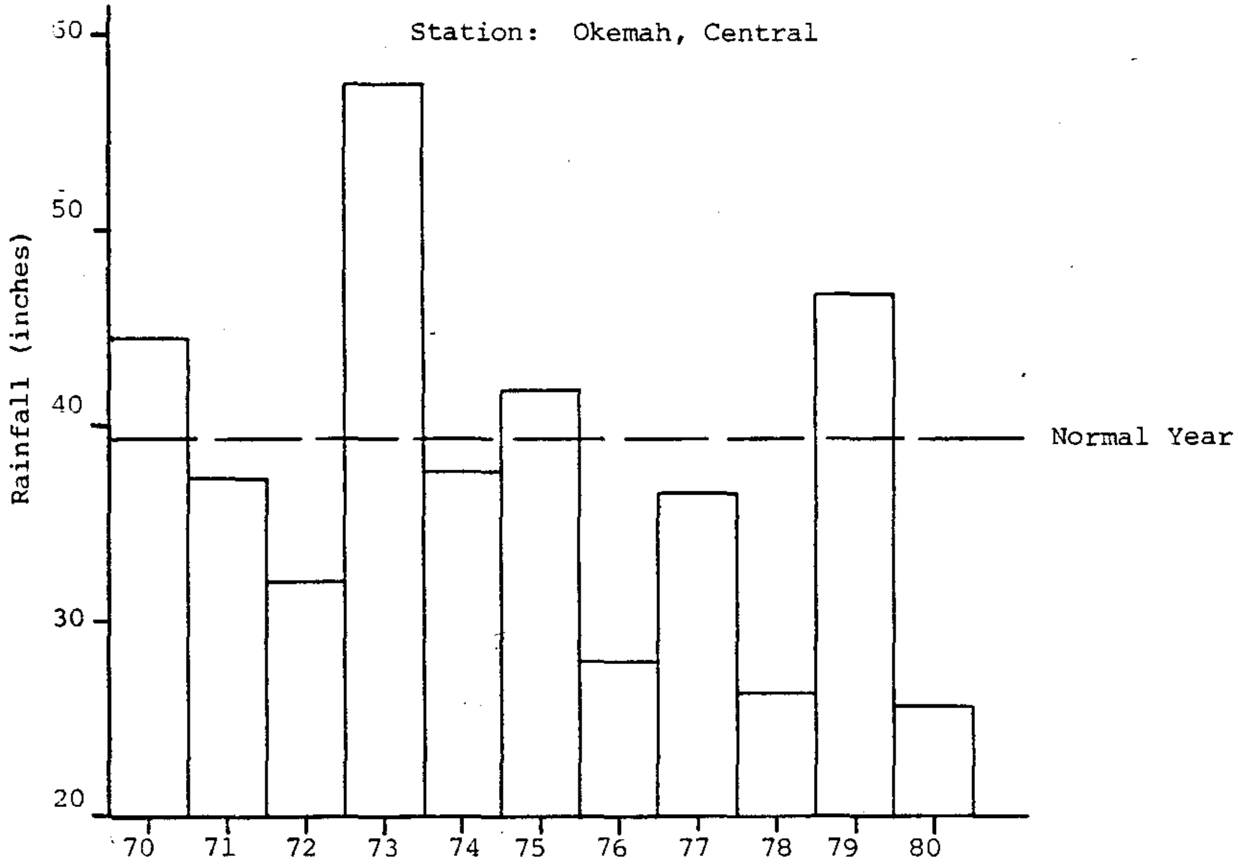


Figure 20. Mean Annual Precipitation for Water Years 1970-1980.

Station: Pauls Valley, South Central

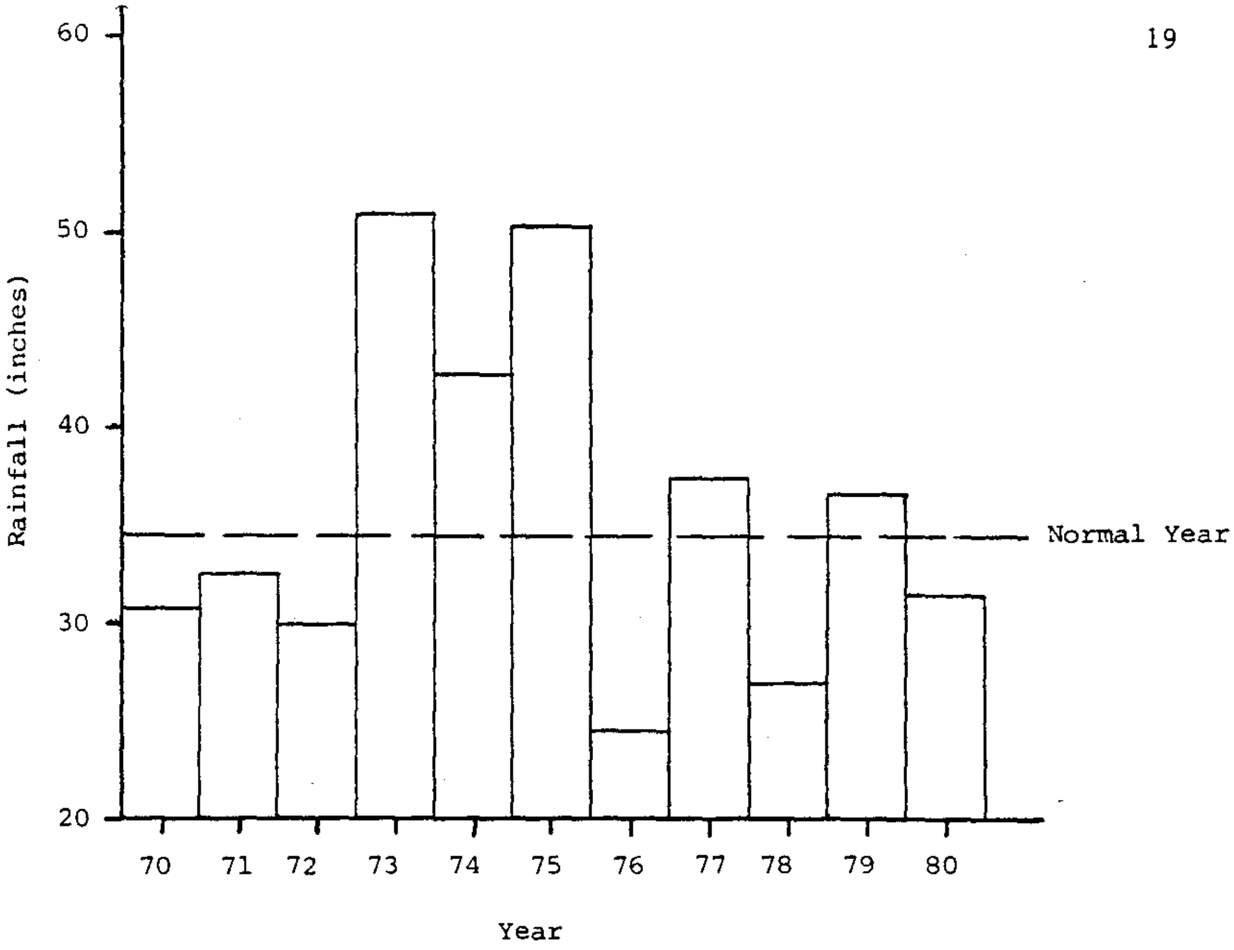
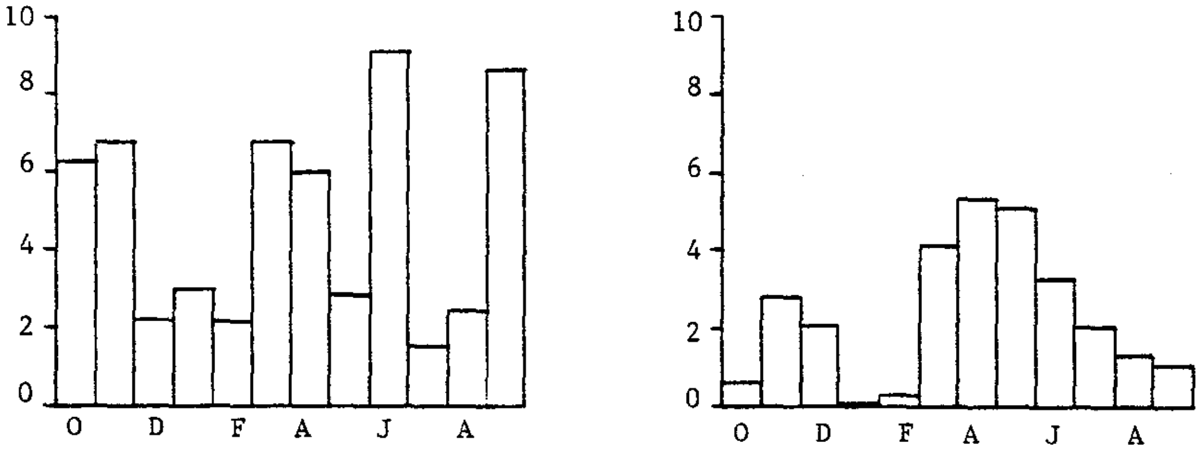
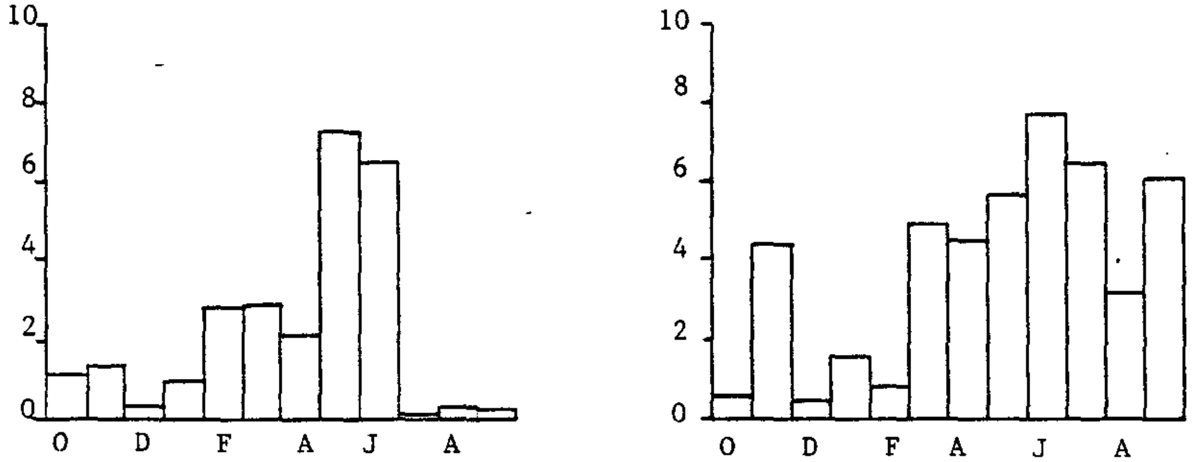


Figure 21. Mean Annual Precipitation for Water Years 1970-1980.



Water Year 1973

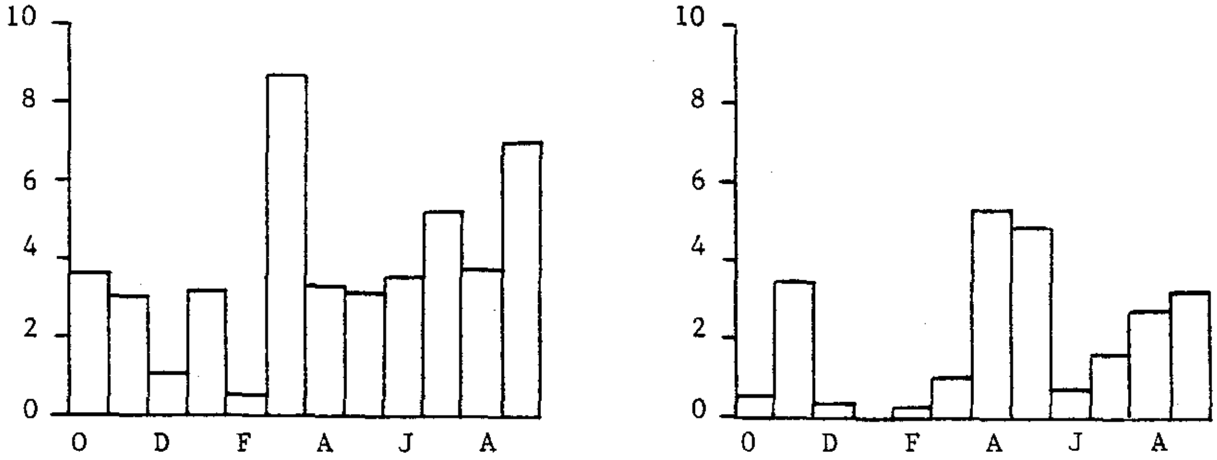
Water Year 1976



Water Year 1978

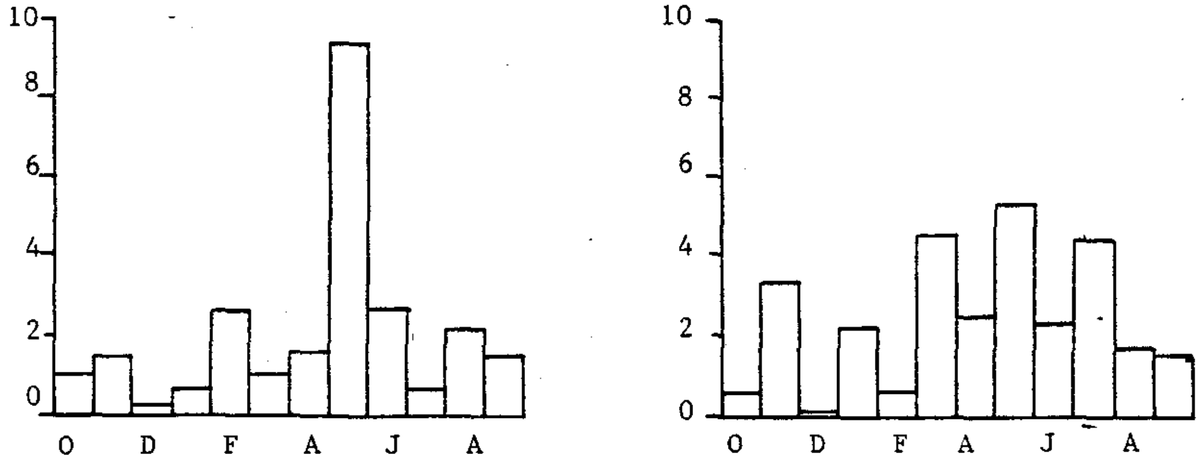
Water Year 1979

Figure 22. Okema Monthly Precipitation for Water Years 1973, 1976, 1978, 1979.



Water Year 1973

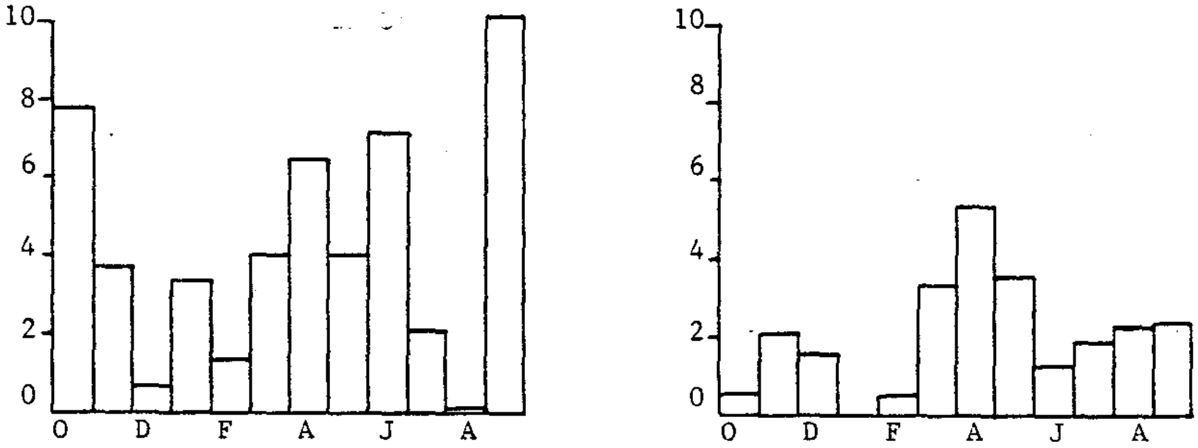
Water Year 1976



Water Year 1978

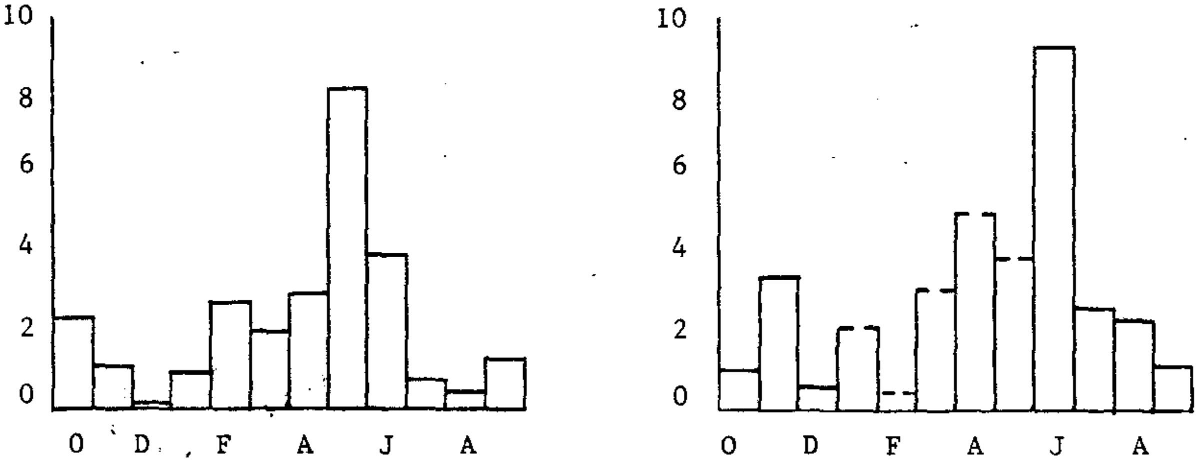
Water Year 1979

Figure 23. Monthly Precipitation for Water Years 1973, 1976, 1978, 1979 at Enid.



Water Year 1973

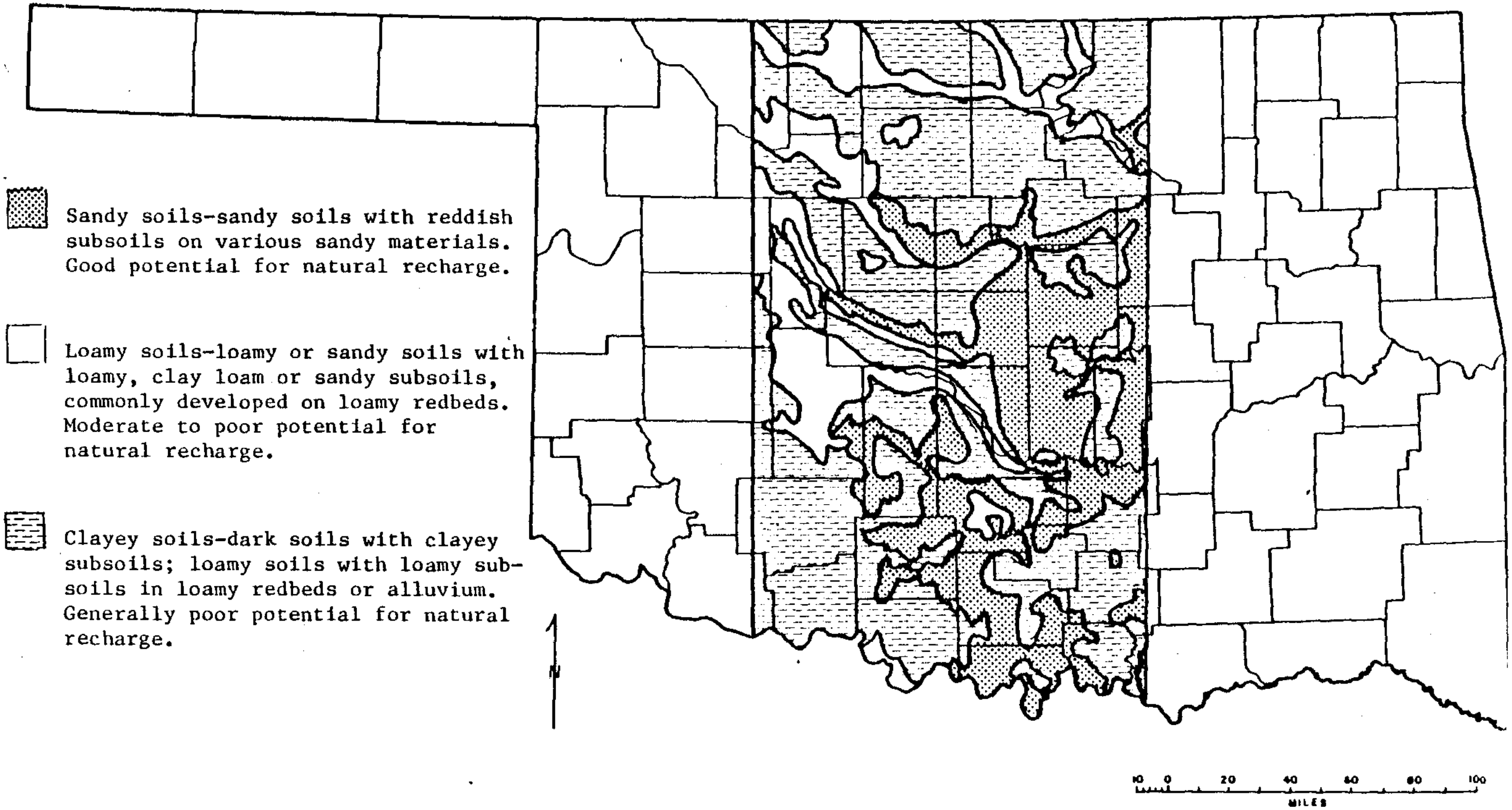
Water Year 1976



Water Year 1978

Water Year 1979
*Data inferred and based
on nearby gage

Figure 24. Paul's Valley Monthly Precipitation for Water Years 1973, 1976, 1978, 1979.



▩ Sandy soils-sandy soils with reddish subsoils on various sandy materials. Good potential for natural recharge.

☐ Loamy soils-loamy or sandy soils with loamy, clay loam or sandy subsoils, commonly developed on loamy redbeds. Moderate to poor potential for natural recharge.

▤ Clayey soils-dark soils with clayey subsoils; loamy soils with loamy subsoils in loamy redbeds or alluvium. Generally poor potential for natural recharge.

Figure 25. Genralized soils map for Central Oklahoma.

in Table 1. Because of the distribution pattern of precipitation, some areas had more rainfall during 1976 than during 1978. In this case the lower value was used for the dry period. Furthermore, since precipitation tends to increase southeastward, higher recharge rates south of the Washita River probably reflect this difference. Data for water year 1979, which probably closely reflects he long term average is shown in Table 2.

Other than the large basins (Arkansas, Cimarron, North and South Canadian, Washita) only one water course (Little River) was recorded by more than one gage. Records indicate a substantial recharge rate increase from west to east. The flow recorded at three gages on Little River are regulated by Lake Thunderbird. Nonetheless, since all gages are below the lake, the effect of regulation is cancelled. Two gages lie within the outcrop are of the Garber-Wellington (plate 1). The upstream gage (2300) has a 257 square mile drainage basin as compared to the downstream gage (2305), which is 456. On the average the effective recharge rate between the upstream and downstream gages is twice as large as that above the upper gage during wet periods and more than 6 times greater during normal (1978) and dry years (1976).

A particularly useful method for evaluating streamflow consists of relating the discharge to the size of the drainage basin (cfs/sq. mi.). During water year 1979 the upper gage on Little River (2300) had a mean daily flow of 7.51 cfs and the lower gage (2305) had a flow of 65.5 cfs, which represents a considerable increase in discharge. When divided by the size of the drainage basin, in order to determine the flow index, the values are .029 and .144 cfs/sq. mi. respectively. During the 90% flow, the flow equalled or exceeded 90% of the time, these values are considerably smaller but the general pattern continues. During 1973 they were .0000039 cfs/sq. mi. and .0000088 respectively, and in 1976 they were .000012 and .000029. In 1979,

Table 1

Information on stream regulation

Station Number	Remarks
1510-	Some regulation by Great Salt Plains Lake
1520-	Some regulation at low flow by Lake Carl Blackwell. Small diversion made from research for minicipal supply.
1525-	Some regulation by John Martin Research Co. Great Salt Plains Lake.
2291-	Extreme low flow sustained by sewage from Norman, occasional regulation by research in Texas and New Mexico.
2300-	Flow completely regulated by flow from Lake Thunderbird.
2305-	Flow regulated or diverted by Lake Thunderbird.
2310-	Flow regulated by Lake Thunderbird.
2395-	Some regulated by Canton Lake.
2400-	Canal from Canadian River to Lake Hefner.
2415.5-	Low flow sustained by Oklahoma City sewage.
3274.9-	Small diversions above station for irrigation
3280.7-	Flow regulated by flood-retarding structures, some diversions for irrigation above station.
3281-	Regulated by Fort Cobb, Foss Research flood-retarding structure.
3285-	Same as above, some irrigation diversions above station.
3297-	Flow regulated by flood-retarding structure and lakes.

		Recharge rate, gpd/sq. mi., inches					
Station Number		Fixed Interval		Sliding Interval		Local Min.	
Wildhorse Ck	3297	83,000,	1.74	67,000,	1.41	15,000,	.32
Winter Ck	3280.7	134,000,	2.83	143,000,	3.02	61,000,	1.29
Little Washita	3274.9	101,000,	2.13	99,000,	2.09	56,000,	1.18
Dry Ck	2430	65,000,	1.38	67,000,	1.41	12,000,	.26
Deep Fork*	2423.5	396,000,	8.33	396,000,	8.32	257,000,	5.4
Little River	2300	13,000,	.28	13,000,	.29	1,354,	.03
Little River	2305	73,000,	1.54	59,000,	1.25	33,000,	.70
Little River	2310	111,000,	2.35	107,000,	2.27	22,000,	.46
Walnut Ck	2293	113,000,	2.38	115,000,	2.42	54,000,	1.15
Council Ck	1630	181,000,	3.82	175,000,	2.70	19,000,	.42
Skeleton Ck	1605	101,000,	2.14	97,000,	2.05	25,000,	.54
Black Bear Ck	1530	100,000,	2.11	99,000,	2.10	14,000,	.31
Salt Fork	1510	73,000,	1.53	70,000,	1.48	4,470,	.09
Chickaskia R	1520	103,000,	2.18	105,000,	2.21	20,000,	.43

*Influenced by discharge of sewage effluent

Table 2. Effective ground-water recharge rates for water year 1979.

however, they were reversed (.0000075 and .0000022, respectively), very likely because of diversion for irrigation.

Regardless of the technique used, it is evident that the flow increases downstream at a rate that is not uniform throughout the drainage basin. This indicates that natural recharge to the Garber-Wellington in the basin of Little River is larger than elsewhere. It also indicates that the aquifer in this area is full to overflowing and that it discharges into streams.

Elsewhere an analysis can be provided only in general terms because of the limited number of gages, the unusually large size of the drainage basin or external effects on the stream brought about by regulation or the discharge of effluent. For example, gage 2423.5 on Deep Fork provides records that indicate a recharge rate that is about four times larger than surrounding stations (plate 1). The high and consistent flow is the result of discharge of municipal sewage effluent into the stream.

The very large basins (Arkansas, Cimarron, North and South Canadian, and Washita) cannot be adequately examined because the computer analysis results in values that are much too low. The computer program is based on the assumption that natural recharge occurs, at least in a general way, more or less uniformly throughout the basin. In these basins, however, two distinctly different types of strata appear--consolidated rocks of relatively low permeability and alluvial or sand dune deposits that are quite permeable. Presently it is not possible to separate the streamflow into the quantities derived from the different strata. Eventually it should be possible to do this with a more refined program that is based in part on differences in water quality. On the other hand, it isn't necessary to use data from gages on the major rivers because their gaged tributaries provide the same information and it is influenced by far fewer externalities.

however, they were reversed (.0000075 and .0000022, respectively), very likely because of diversion for irrigation.

Regardless of the technique used, it is evident that the flow increases downstream at a rate that is not uniform throughout the drainage basin. This indicates that natural recharge to the Garber-Wellington in the basin of Little River is larger than elsewhere. It also indicates that the aquifer in this area is full to overflowing and that it discharges into streams.

Elsewhere an analysis can be provided only in general terms because of the limited number of gages, the unusually large size of the drainage basin or external effects on the stream brought about by regulation or the discharge of effluent. For example, gage 2423.5 on Deep Fork provides records that indicate a recharge rate that is about four times larger than surrounding stations (plate 1). The high and consistent flow is the result of discharge of municipal sewage effluent into the stream.

The very large basins (Arkansas, Cimarron, North and South Canadian, and Washita) cannot be adequately examined because the computer analysis results in values that are much too low. The computer program is based on the assumption that natural recharge occurs, at least in a general way, more or less uniformly throughout the basin. In these basins, however, two distinctly different types of strata appear--consolidated rocks of relatively low permeability and alluvial or sand dune deposits that are quite permeable. Presently it is not possible to separate the streamflow into the quantities derived from the different strata. Eventually it should be possible to do this with a more refined program that is based in part on differences in water quality. On the other hand, it isn't necessary to use data from gages on the major rivers because their gaged tributaries provide the same information and it is influenced by far fewer externalities.

From a natural recharge point of view the Garber-Wellington outcrop area can be divided into three rather broad zones. Zone A extends southward from the Kansas-Oklahoma border to the southern part of Noble County. Here the major or gaged water courses include the Arkansas and Chikaskia River, Salt Fork and Black Bear Creek. In this region effective ground-water recharge rates during a wet year (1973) were about 102,000 gpd/sq. mi. (2.1 inches) and during a normal year (1979) were about 92,000 gpd/sq. mi. (1.9 inches).

Zone B extends southward from the northern part of Payne County to the headwaters of Little River in Cleveland County. Here recharge during 1973, 1976, and 1978 was about 58,000 gpd/sq. mi. (1.2 inches), 10,000 (.21 inches) and 21,000 (.44 inches) respectively. These data are representative of the western less permeable part of the study area and the rates are quite likely larger eastward. During 1979, however, which is more typical of a normal year although wetter, the average rate is about 105,000 gpd/s.mi. (2.21 inches).

Zone C extends southward through the Wildhorse Creek basin. Recharge rates in Zone C during wet, dry, and normal years average about 99,000 gpd/sq. mi. (2.7 inches), 23,000 (.48 inches), and 41,000 (.86 inches), respectively. Data for individual sites are shown in plate 1. Recharge in 1979 averaged about 92,000 gpd/sq.mi. (1.9 inches) in the Garber Wellington outcrop area.

The average effective recharge rates discribed above are influenced to a large degree, by precipitation events and patterns. Since annual precipitation increases towards the southeastern part of the state, the higher recharge rates along and south of the Washita River basin probably reflect this difference. Furthermore, precipitation patterns during the years studied were not uniform and fluctuated rather widely from one place to the next. Considering all the data, it would appear that the average effective ground-water recharge rate for the unconfined part of the Garber-Wellington

Station No.	1973	1976	1978	1979
1510	[1]2.51	0.56	0.62	
	[2]2.31	0.56	0.59	
	[3]1.49	0.53	0.46	
1520	2.37	0.85	1.11	
	2.17	0.87	1.12	2.18
	1.75	0.82	1.08	2.21
				.43
1525	1.40	0.40	0.56	
	1.26	0.42	0.57	
	1.07	0.32	0.53	
1530	2.05	0.26	0.21	2.11
	2.10	0.26	0.22	2.10
	1.09	0.23	0.18	.31
1605	0.99	0.50	0.29	2.14
	1.01	0.50	0.30	2.05
	0.91	0.46	0.27	.54
1610	0.76	0.21	0.18	
	0.63	0.22	0.17	
	0.57	0.21	0.18	
1630	1.35	0.31	0.38	3.82
	1.34	0.31	0.45	3.70
	1.20	0.30	0.30	.42
		(1967)	(1968)	
2291	0.09	0.05	0.10	
	0.09	0.04	0.10	
	0.09	0.02	0.04	
2293	2.84	1.17	0.28	2.38
	2.84	1.16	0.30	2.42
	2.82	1.10	0.24	1.15

[1] Fixed Interval

[2] Sliding Interval

[3] Local Minima

Table 3. Effective ground-water recharge, in inches

Station No.	1973	1976	1978	1979
2300	1.23	0.05	0.03	.28
	1.39	0.05	0.03	.29
	0.59	0.05	0.03	.03
2305	2.90	0.33	0.18	1.54
	3.03	0.33	0.17	1.25
	2.65	0.32	0.13	.70
2310	3.70	0.53	0.48	
	3.62	0.55	0.50	
	3.39	0.47	0.40	
2395	0.10	0.03	0.05	
	0.10	0.04	0.05	
	0.18	0.03	0.04	
2415.5	0.25	0.10	0.09	
	0.23	0.10	0.09	
	0.21	0.10	0.09	
2423.5	5.11	3.51	3.29	8.33
	5.12	3.50	3.30	8.32
	4.75	3.48	3.20	5.40
2430	1.32	0.98	0.17	1.38
	1.32	0.96	0.16	1.41
	1.25	0.90	0.15	.26
3274.9	1.60	1.45	0.80	
	1.64	1.44	0.82	
	1.50	1.39	0.77	
			(1975)	
3280.7	4.57	1.34	5.86	2.13
	4.45	1.36	6.30	2.09
	3.74	1.22	4.80	1.18
			(1968)	
3281	0.78	0.66	0.78	
	0.70	0.65	0.77	
	0.66	0.62	0.28	
3285	0.94	0.71	0.70	
	0.90	0.71	0.69	
	0.78	0.68	0.69	
3297	2.38	0.90	0.84	1.74
	2.39	0.84	0.70	1.41
	2.16	0.69	0.49	.32

Table 3. (cont.). Effective ground-water recharge, in inches

aquifer is about 100,000 gpd/sq.mi. or about 2.11 inches. On most appraisals, this is the rate that should be considered. Recharge rates expressed in inches are shown in Table 3.

The frequency of droughts and wet periods also have a subtle effect on the hydrologic system. For example, a wet year following months or years of dry weather will not influence streamflow or ground-water recharge as much as a wet year following a normal or wet year. In part this is due to a large share of the water being used to replace the soil-moisture dificiency and there may be little excess for surface runoff or ground-water recharge. Resultingly there may be a large difference in calculated effective recharge rates from one year to the next or from place to place.

The preliminary estimates of effective ground-water recharge rates described herein reflect only a short time span and, consequently, are subject to revision. Another project is presently underway by the author to evaluate rates using a 10-year continuous data base. This study will result in effective recharge rates that are less influenced by uncommon precipitation events or periods. On the other hand, recharge rates during dry years are important, particularly for planning purposes, because it is during dry periods that wells must withdraw largely from storage.

Recharge rates for other areas in Oklahoma have been determined by a variety of methods by graduate students in the Department of Geology at Oklahoma State University. Generally the rates were based on computerized ground-water flow models and thus recharge was not actually measured but rather estimated by calibrating each model. The calibrations were based on long term averages. In most cases only the most permeable areas were modeled.

The Enid Terrace was investigated by Beausoleil (1981). Using well hydrographs and precipitation data for this model, he concluded that the natural recharge rate was about 2.3 inches/year (109,500 gpd/mi.sq.). Lyons (1981) in his study of the Elk City-Washita area, calculated a recharge rate of 3.92 inches/year (186,630 gpd/mi.sq.), which as 14.1% of the long term precipitation rate. The North Fork of the Red River was investigated by Paukstartis (1982). He estimated a long term recharge rate of 2.28 inches/year (108,550 gpd/mi.sq.), which was equivalent to 9.4% of the total runoff. Shipper, whose work is still in progress, studied part of the Washita basin. His preliminary estimate of recharge through permeable alluvial deposits is 3.3 inches/year (157,100 gpd/mi.sq.).

References Cited

Beausoleil, Y. J., 1981. A ground-water management model for the Enid isolated terrace aquifer in Garfield County, OK: Unpublished M.S. thesis, Department of Geology, Oklahoma State University, 66 p.

Lyons, T. D., 1981. A ground-water management model for the Elk City aquifer in Washita, Beckham, Custer and Roger Mills Counties, OK: Unpublished M.S. thesis, Department of Geology, Oklahoma State University.

Paukstratis, E. J., 1981. Computer simulation of the alluvial aquifer along the North Fork of the Red River in southwestern Oklahoma: Unpublished M.S. thesis, Department of Geology, Oklahoma State University, 111 p.

Pettyjohn, W. A. and R. J. Henning, 1979. Preliminary estimate of ground-water recharge rates, related streamflow and water quality in Ohio: Ohio State University Water Resources Center, Rept. 552, 323 p.

U. S. Geological Survey, Water resources data for Oklahoma, 1973, 1976, 1978 and 1979: U. S. Department of Interior, Geological Survey.